INVERSE COMPTON SOURCES ON THE BASIS OF ELECTRON ACCELERATORS WITH BEAM ENERGY RECOVERY

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Abstract

In inverse Compton Source, photons in Roentgen range originate from visible light laser photons scattered back on electrons with the energy of dozens MeV. Several schemes are suggested in the paper, beam energy recovery conception being the common idea of all of them. The first one is based on synchrotron with flat part of guiding magnetic field. Being accelerated, electron bunch interacts with photon bunch of free electron laser mounted on straight paths of the accelerator, then is decelerated during falling down period of magnetic field cycle, and extracted at low energy from synchrotron to absorb in beam dump. This measure decreases background that originates from bremsstrahlung of lost electrons inherent to classical schema with linear accelerator and storage ring. Two other schemes use superconducting linac that produces relativistic electron bunches which energy is recovered after use, free electron laser (FEL) driven by bunches from linac being used to produce photons bunches for source. In one scheme the same electron bunches are use to drive FEL and inverse Compton Source, while in the other one beam splitting technique is suggested. It is based on beam energy modulation with subsequent separation of successive bunches. The expected self excitation inverse Compton sources parameters are estimated followed by critical issues discussion for all schemes suggested.

INTRODUCTION

They say that back Compton scattering takes place when part of electromagnetic radiation is reflected backward by relativistic electron moving in the direction opposite to electromagnetic wave flow. In spite of low cross section of this process the devices based of this phenomenon find practical applications due to narrow spectrum of the radiation. The maximum energy of back scattered photons scales as square of electron energy thus allowing the radiation in Roentgen wave range obtaining scattering visible light on the electron bunch with the energy of several dozens of MeV. The availability of power lasers as well as charged bunch formation technique that came from accelerator based technique makes it possible Compton sources developing with intensities quite sufficient for applications.

Classical scheme of the light source based on the back Compton scattering represents optical cavity and electron storage ring arranged in such a way that these have an interaction point [1], one turn time circulations of electron bunch in storage ring and photon bunch in the cavity being synchronized to cross this point at the same moment. This arrangement is complemented by electron linac with injection system and a laser with appropriate cavity excitation system. The project based on this scheme had already realized successfully and might serve as prove of principle. It seems quite natural in further study and the development of such Roentgen source to move from oscillator scheme to self oscillator, and one of the main elements of existing equipment namely electron accelerator might be a basis for similar extension.

In this paper, we discuss the possibility to develop back Compton scattering source on the basis of free electron laser (FEL) and the energy recovery accelerator that drives this FEL. Three schemes are studied, one of these being built on the basis of electron synchrotron while two others on the basis of superconducting rf linac. In these schemes, electron bunches from an accelerator are used to drive FEL and to be a target for photons generated in the FEL. The critical issues of all schemes as well their advantages and shortcomings are discussed.

THE MAIN FEATURES OF FEL AND BACK COMPTON SCATERING

Fig.1 illustrates schematically back Compton scattering process. There is an incident electromagnetic wave of frequency ω with the energy density U_{ins} and relativistic electron with relative energy γ moving towards electromagnetic wave.

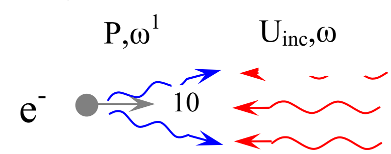

Fig.1 Back Compton scattering

The following formulae take place

$$\omega' \cong 4\omega\gamma^2,\quad P \cong \frac{4}{3}\sigma_T c\gamma^2 U_{inc}. \qquad (1)$$

Here P is scattered wave power calculated per one electron, ω' is the frequency of scattered wave, c is light velocity and σ_T is so called Thomson cross section of an electron:

$$\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{m_e c^2}\right)^2 \approx 6{,}65\times 10^{-25}\,\text{см}^2, \qquad (2)$$

where e, m are the electron charge and its mass.

It follows from the above formulae that inferior limit of the total number of scattered photons might be represented in the form

$$N \cong \frac{\sigma_T}{3\sigma_{ph}} N_{ph} N_e, \qquad (3)$$

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where N , N_{ph} and N_e are number of scattered photons, number of photons in incident light bunch and number of electrons in electron bunch that scatters incident light bunch. It is assumed all photons in scattered bunch to have the same frequency defined by formula (1) that is quite justified for estimations. It is also assumed that target electrons covered completely by incident photon bunch.

Here we remind briefly principle of free electron laser. Schematically its arrangement is shown on fig.2.

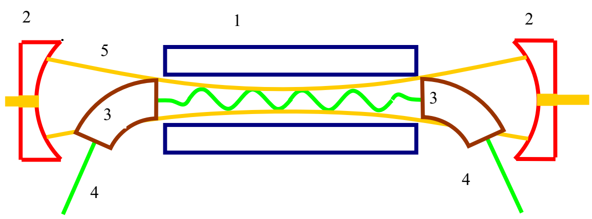

Fig.2. FEL layout. 1 – undulator, 2 – mirror, 3 – magnet, 4 – electron beam, 5 – optical mode envelope, 6 – laser radiation

Electron beam with the help of bending magnet is injected on undulator axis. Cavity optical mode interacts with moving electrons in undulator area. One path gain of electromagnetic wave might estimated from formula

$$G = 4\sqrt{2}\pi N\lambda_w^{1/2}\lambda_s^{3/2}\frac{K^2}{(1+K^2)^{3/2}}\frac{i}{si_A}\left(\frac{\Delta\omega_s}{\omega_s}\right)_t^{-2} \quad (4)$$

Here λ_w - undulator period, λ_s - generated radiation wavelength

$$\lambda_s = \frac{\lambda_w}{2\gamma^2}(1+K^2) \quad (5)$$

$$K = eH_{W0}\lambda_w / 2\pi mc^2 \quad (6)$$

H_0 - the amplitude of periodic magnetic field on undulator axis. $\Delta\omega$ is line widening, soused by undulator finite length, finite length of the radiated electron bunch and non zero value of bunch longitudinal emittance (non zero energy spread). s is bunch cross section.

$$\left(\frac{\Delta\omega_s}{\omega_s}\right)_t^2 = \left(\frac{\Delta\omega_s}{\omega_s}\right)_h^2 + \left(\frac{\Delta\omega_s}{\omega_s}\right)_i^2 \quad (7)$$

$$i_A = mc^3 / e = 17\kappa A \quad (8)$$

$$\left(\frac{\Delta\omega_s}{\omega_s}\right)_t^2 = \left(\frac{1}{N}\right)^2 + \left(\frac{\lambda_s}{2l_e}\right)^2 \quad (9)$$

$$\frac{\Delta\omega}{\omega} = 2\frac{\Delta E}{E} \quad (10)$$

To move from oscillator to self oscillator scheme of Compton light source we suggest the arrangement shown schematically on fig.3.There is a traveling wave cavity with two active arms. One of these is in FEL active part area where the beam-optical mode interaction takes place providing FEL generation process. The second one serves to provide electron bunch-optical train collisions. Depending on electron beam propagation direction an optical cavity might be of different configuration. For the case of the electron beams moving in opposite direction in two cavity arms just shown on fig.3 light lines have intersection area. If electron bunches move in the same direction in both arms optical train represents a rectangular with successive reflection from mirrors in rectangular vertexes.

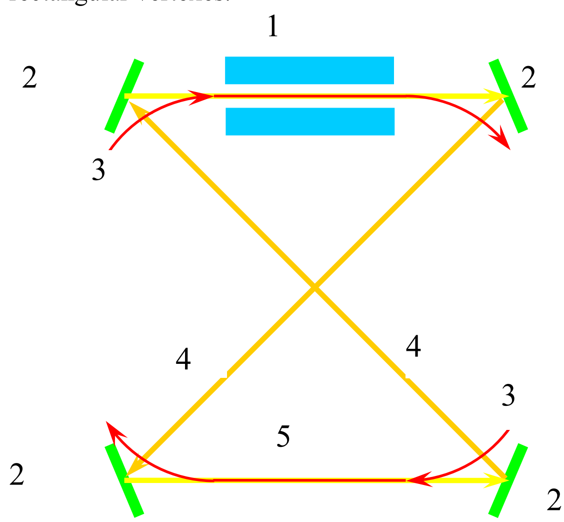

Fig.3. Possible electron beam-light optics configuration in self excitation back Compton scattering light source.
1 – FEL undulator, 2 – mirrors, 3 – electron beams trajectories, 4 – light path, 5 – electron bunch-light bunch collisions area.

BACK COMPTON SCATTERING LIGHT SOURCES

Fig. 4. represents a back Compton scattering light source on the basis of electron synchrotron. Injected from laser injector electron bunch is accelerated up to maximum energy. At this energy guiding magnetic field has a plateau that provides constant bunch energy during some time. FEL is formed by undulator installed in straight path and four mirrors cavity. All lengths are chosen to realize bunch-light collisions in opposite straight path. Electron bunch strikes moving in opposite direction light train generated in undulator area. Electron bunch decrease its energy during falling down phase of magnetic field cycle. The energy recovery phase is stopped by bunch extraction. Extracted at low energy bunch is directed to a dump.

Synchrotron scheme seems to have an advantage as compared to a linac-storage ring configuration. First, additional accelerator (that is used for electron bunch injection) is not required and second beam energy recovery process reduces background.

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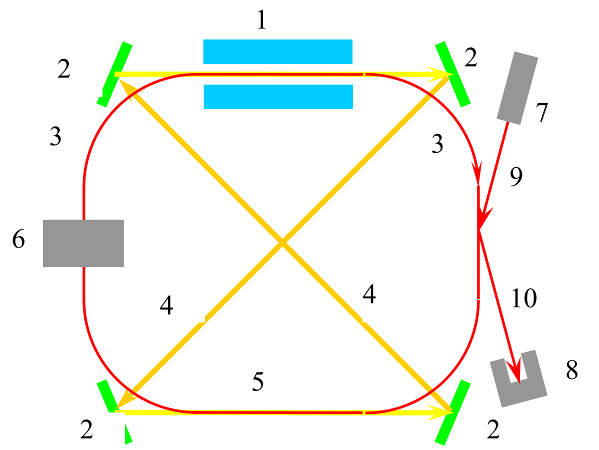

Fig.4. Back Compton light source on the synchrotron basis. 1 – FEL undulator, 2 – mirrors, 3 – electron beams trajectories, 4 – light path, 5 – electron bunch-light bunch collisions area, 6 – rf cavity, 7 – injector, 8 – dump, 9 – injected beam, 10 – extracted beam.

Shown on fig. 5 light source scheme is built on the basis of superconducting rf linac with beam energy recovery. Electron bunches from accelerator enter the active area of free electron laser consisting of undulator and optical cavity similar to that used in synchrotron based scheme. Leaving undulator area bunches are rotated by magnet arrangement (not shown) and second time traverse the cavity where interact with light trains. Then used bunches are directed to linac entrance in decelerating rf field phase thus transferring kinetic energy to rf field. Being decelerating down to injecting energy the bunches are deflected out of linac axis to be absorbed in beam dump.

A feature of the scheme represented on fig.6 consists of the use undisturbed beam in both active arms of four mirrors optical cavity. Opposite to the configurations just discussed the electron bunches move in the same direction in both arms while light trains in opposite directions. To have two beams from the same linac additional cavity is used at linac exit, the main linac and additional cavity being operated at frequencies bounded by condition

$$2n\omega_2 = (2n+1)\omega_1, \qquad (11)$$

where ω_1, ω_2 are the frequencies of linac and cavity respectively and n is the number of rf periods between two successive bunches. Thus successive bunches traverse the cavity in accelerating and decelerating phases that provides beam energy modulation and subsequent beam splitting with appropriate magnet arrangement. After interaction in optical cavity with light bunches two electron beams are combined by similar magnet arrangement to form again one line, while similar additional cavity on linac axis equalizes successive bunches energy. Then used beam enters the linac in decelerating phase and energy recovery process is ended by low energy beam absorption in beam dump.

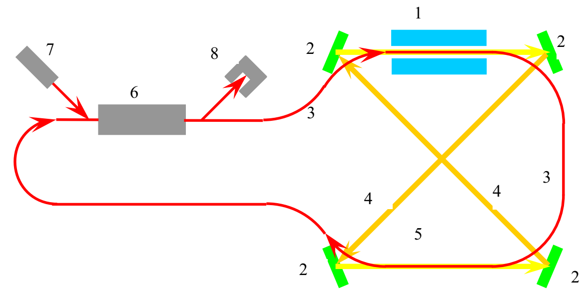

Fig.5. Back Compton light source on the basis of rf superconducting linac. 1 – FEL undulator, 2 – mirrors, 3 – electron beams trajectories, 4 – light path, 5 – electron bunch-light bunch collisions area, 6 – rf linac, 7 – injector, 8 – dump.

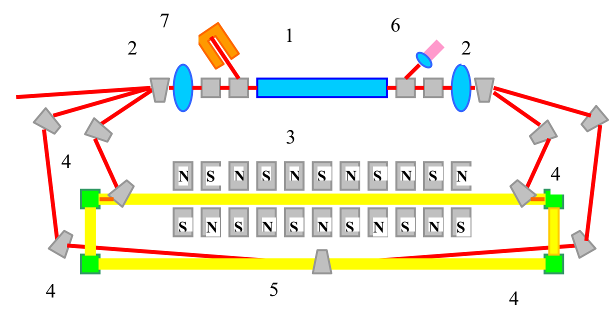

Fig.6. Back Compton light source on the basis of rf superconducting linac and beam splitting technique. 1- rf linac, 2 – rf cavity, 3- FEL undulator, 4 – traveling wave resonator mirror, 5 – beam-light interaction area, 6 – injector, 7 – beam dump.

To estimate the number of back scattered photons we assume bunch current to be 100 A ($N_e \cong 10^{10}$), bunch energy 100 MeV, bunch pulse duration 10 psec $\sigma_{ph} = 1mm^2$ and 1 percent of FEL efficiency. This corresponds to approximately 10^{18} photons in the light train moving in the cavity. According formula (3) this gives 10^5 Roentgen photons per one collision.

CONCLUSION

We have considered three schemes of Roentgen light sources based on free electron lasers, back Compton scattering and energy recovery technique. In spite of apparent complexity these schemes might be useful for small multi purposes facilities.

REFERENCES

[1] Z.Huang, R.D.Ruth. Phys. Rev. Letters, Volume 80, Number 5, 2 Feb. 1998. pp. 976-979.
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